MARS PATHFINDER ACTIVE THERMAL CONTROL SYSTEM: GROUND AND FLIGHT PERFORMANCE OF A MECHANICALLY PUMPED COOLING LOOP

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ABSTRACT

The Mars Pathtinder spacecraft was launched on December 3, 1996. The major objectives of the Mars Pathfinder are to demonstrate low cost entry, descent, and landing technologies for use in the subsequent flights to Mars. Further, the Pathfinder includes a lander that will operate for one month on the Martian surface conducting surface science studies assisted by a microrover.

The temperature control requirements of the spacecraft during launch, cruise, and Martian surface operation necessitated the design of an active thermal control system for the heat rejection system. A mechanically pumped single phase Freon cooling loop is used to transfer excess heat generated in the electronics shelf to an external radiator. This is the first time a mechanically pumped cooling loop has been used on a planetary mission. Several lessons were learned from this experience about the design and operation of the active cooling loops. These lessons are expected to help building lighter and higher performance loops for the future spacecraft missions. This paper describes the performance of the mechanically pumped cooling loop during ground and flight operations.

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INTRODUCTION

Spacecraft Mission

The Mars Pathfinder spacecraft was launched in December 1996 to place a lander on the Martian surface on July 4, 1997. It is the first of a series of spacecraft designed to explore the planet Mars; at least two spacecraft are planned to be sent to Mars every two years for the next fifteen years by the United States, the European Space Agency, and Russia. The major objectives of the Mars Pathfinder are to demonstrate low cost entry, descent, and landing technologies for use in the subsequent flights to Mars. Further, the Pathfinder includes a lander that will operate for one month on the Martian surface conducting surface science studies assisted by a microrover[1].

The Mars Pathfinder flight system is essentially three spacecraft in one. The first part is the Cruise Stage consisting of power, propulsion, and navigation equipment needed to take the spacecraft to Mars. The second part is the Entry, Descent, and Landing stage consisting of an Aeroshell and Deceleration Module to help the Lander safely enter the Martian environment and land on the surface. The third part is the Lander that houses the instruments including the Sojourner microrover.

A schematic of the spacecraft highlighting the thermal control elements is shown in Figure 1. The top part of the spacecraft is called the cruise stage and is used during the cruise part of the mission. This stage is separated from the rest of the spacecraft just before it enters the Martian atmosphere. The lander part of the spacecraft enters the atmosphere and the ablative aeroshell protects the equipment inside from the entry aerodynamic heating. The heatshield is detached and discarded once the lander is slowed down by a deployed parachute. The lander is further slowed down by a retro rockets and the airbags surrounding the lander are inflated. The airbags cushion the landing impact and are vented and retracted once the lander comes to a standstill. The lander deploys its selfrighting petals and exposes the solar arrays, insulated electronics, and the rover to the Martian atmosphere. The rover is released and one month of Martian surface exploration starts.

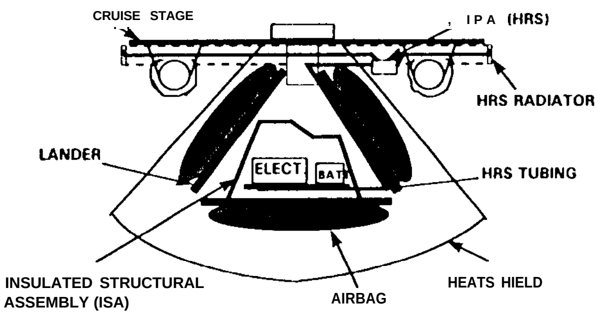

Figure 1. Mars Pathfinder Spacecraft Configuration

The same communication and data analysis electronics are used both during cruise and landed operations. This equipment is located on the base petal of the lander and is completely enclosed in a very high performance insulation to conserve heat during the cold Martian nights (as cold as -80 C). During cruise, the same equipment is operated continuously at about 90 Watts of power to communicate with ground. Because of 1) power level, 2) high temperature (15 C near earth) outside the insulated enclosure, and 3) additional insulation from the stowed airbags, it is very difficult to passively dissipate the heat. These conditions in the spacecraft configuration necessitated a need for a heat rejection system (HRS) for Pathfinder. The main functions of HRS were to transfer heat from the lander during cruise and minimize heat leak from the enclosure during Martian nights.

ACTIVE COOLING SYSTEM

Various options were examined for the HRS that would meet the spacecraft requirements. These options included mechanical thermal switches, diode heat pipes, variable conduction heat pipes, and fixed conduction heat pipes with mechanical detachment. After a six-month study evaluating these options, a mechanically pumped cooling loop was selected for the HRS. A detailed description of the evaluation process and the and cooling loop was given in an earlier paper[2].

The key elements of the mechanically pumped cooling loop are the following:

1. Integrated Pump Assembly (lPA)
2. Radiator
3. HRS tubing
4. Freon-II working fluid
5. Freon vent system
6. Electronic shelf

A schematic of the HRS system is shown in Figure 2. The IPA, which the key component of the cooling loop, consists of centrifugal pumps, accumulator, thermal control valves, check valves, and the motor control electronics

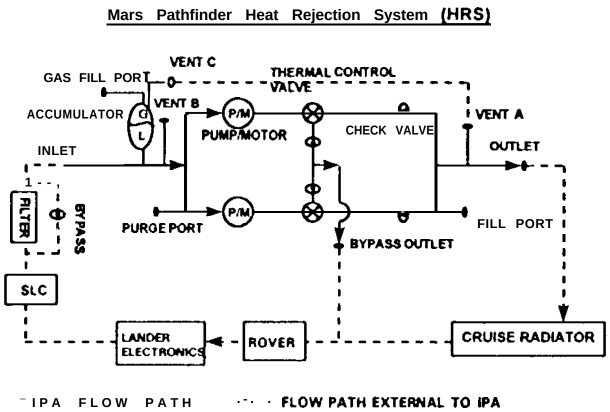

Figure 2. Mars Pathtinder Heat Rejection System

Several engineering tests were conducted to verify performance of the various elements of the cooling loop before the actual flight system was fabricated Along with the performance tests, a long term life test was also done to verify the reliability of the system for the seven-month Mars cruise[4].

The build-up of the flight cooling loop consisted of fabrication of various components separately and installing them on the spacecraft. The IPA was built by an outside contractor and delivered to JPL. The aluminum radiator was built in segments at JPL and the aluminum tubing was brazed to the radiator segments. Similarly the aluminum tubing was brazed to the aluminum electronics shelf. The rest of the cooling loop tubing was made of 304 stainless steel and it was bolted to the spacecraft structure.

One of the major assemblies of the HRS was the structure called the IVSR. This assembly consisted of the IPA, a filter with a bypass check valve, a freon vent system with pyre-actuated valves, and tubing brazed to an aluminum plate for mounting an electronics box called SLC. All these parts were welded in the IVSR structure. There were three tubes coming out of the IVSR -- inlet, outlet and the bypass tubes. This IVSR was designed to be installed onto the spacecraft by three mechanical joints (A-N fittings).

The total mass of the HRS system was 18 kg. The IPA was 8 kg while the freon mass was 2.5 kg and remaining consisted of the radiator, tubing, filter, and the IVSR structural members.

GROUND PERFORMANCE

Several test were done on the cooling loops and their various elements during the fabrication, installation on the spacecraft, and the system level design verification of the spacecraft. Most of the tests done during fabrication were to verify the performance of the I PA components and the whole I PA system. Before installation on the spacecraft, IPA was assembled with a filter and vent system on a structure called IVSR structure.

The key performance tests done on the IPA and its components were to verify the flow rate and pressure head of the pumps and the corresponding current draw. Another important test was to verify the operation of thermal control valve in the specified temperature range and the leakage rate. A third series of tests were on the performance of the accumulator. Several tests on the electronic motor controller were done to verify their electrical performance.

Once the IPA was assembled into IVSR structure, the whole unit was tested for a whole range of performance in ambient conditions. The pumps were run both singly and together and the both hydraulic and electrical measurements were made. The flow rate through the IVSR was varied by valve installed in the set up of the tests. The corresponding pressure head, flow rate, and current draw were monitored. The thermal control valves were cycled and the flow bypass was monitored against the fluid temperature. During these tests, the pumps were operated for a total of about 150 hours. The pump electrical power and pressure head as a function of flow rate is shown in Figures 3 and 4.

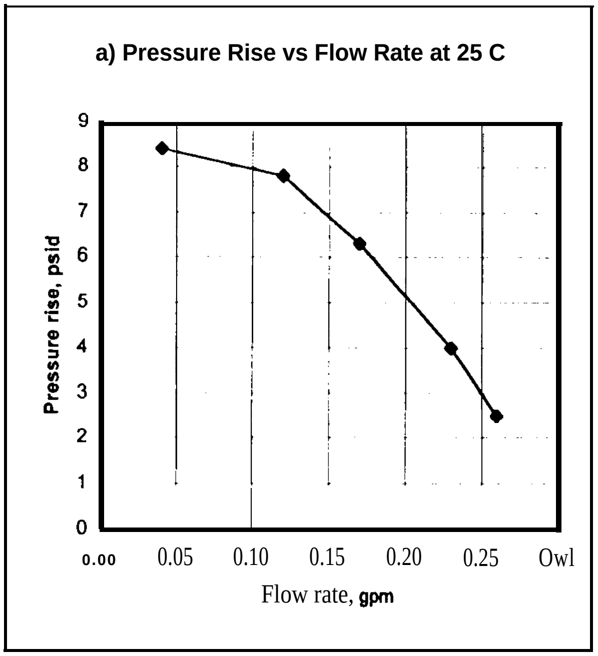

Figure 3. Pressure Rise vs Flow Rate for Each Pump

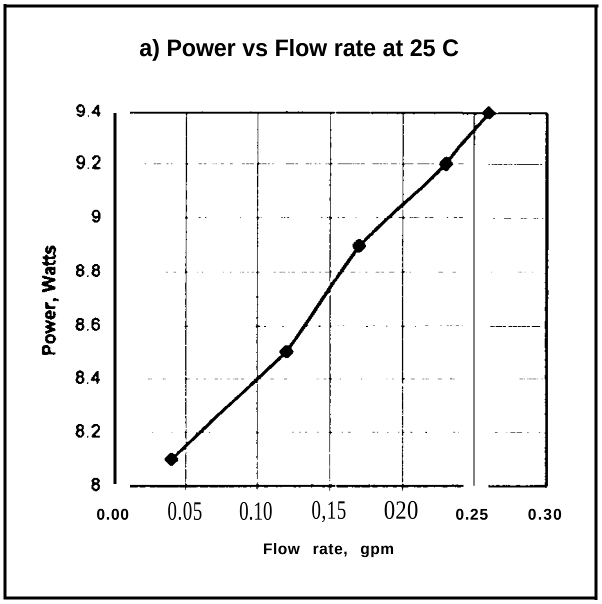

Figure 4. Electrical Power vs Flow Rate for Each Pump

Two types of tests were conducted at the spacecraft level. The first one was to verify the functionality of the IPA in the HRS. In this case, the pumps were turned on and the current draw of the pumps and the temperature of the HRS system at several location were measured. The pressure in the accumulator gas side was also monitored. The pumps were run either singly or together.

The second type was the system-level then-ml vacuum test. In this test, the whole spacecraft went through system level test for two weeks through the entire thermal environment range of the mission. The HRS system operated continuously during the test and HRS temperatures, freon pressure, and the pump/motor current and voltages were monitored during the entire test.

The thermal performance of the spacecraft controlled by the HRS was very close to the analytical predictions made prior to the test. The thermal performance cooling loop was monitored by examining the temperature readouts of the thermocouples placed on the various locations on the cooling loop and the spacecraft. The temperature differential between the electronic shelf and the radiator was about 9 C, as was predicted before the tests. The pump current draw was very close to what was measured earlier during the IPA performance tests.

One of the surprising behavior observed was the cycling of the thermal valves when the shelf outlet freon temperatures fell below O C. During the design of the cooling loop a quick analysis of the thermal valve in the cooling loop was made to see whether any valves would cycle when the temperature fell below OC. It was understood that any cycling would lead to a fluctuation ofa few degrees in the shelf temperatures and cycling duration would be of an hour or so. It was also expected that the thermal capacity of the shelf would dampen these cycles leading to fairly constant shelf temperatures. However, during the thermal vacuum test, it was noticed that shelf temperatures cycled about 2 to 3 C and the there were about six cycles per hour. The conclusions were that during bypass the cooling loop was under damped. A quick calculation showed that the corresponding linear movement of the thermal valve actuator to be less than two roils. Since the wax actuator bellows were life tested for over 50,000 cycles for linear movement of over 50 roils, it was determined not to be a concern.

FINAL FREON LOADING OF HRS

After completing all the system level tests at JPL, the spacecraft was separated into lander and cruise stage and transported to the Kennedy Space Center (KSC). The HRS system was drained of freon before its disassembly at JPL. At KSC, the spacecraft was reassembled and final tests and checkout were conducted. As part of the final assembly procedures, the [IRS was reassembled and charged with freon.

One of the key procedures at this stage was the adjustment of the accumulator for the freon level and also the pressure. The system was designed to maintain an operating pressure which is at least 30 psi above the freon vapor pressure at that temperature. This is prevent any cavitation due to low operating pressure near the centrifugal pump impellers. Therefore it was important that the system was loaded with the right amount of freon at the right pressure at room temperature. This would ensure that the operating pressure at the lowest temperature will still be 30 psi above the freon vapor pressure at that temperature. Similarly, the operating pressure was not to exceed a maximum pressure of 100 psia at the upper temperature limit of the system.

A pressure transducer installed in the accumulator was used for monitoring the pressure during and after the charging of the system. The spacecraft HRS was charged during the last week of October 1996 and the accumulator pressure was monitored on a hi-weekly basis until two weeks before launch to ensure that there were no observable leaks in the system.

FLIGHT PERFORMANCE OF HRS

The HRS system was turned on just before the launch on the pad. Both Pump A and Pump B were turned on and the current draw of the pumps was monitored. The temperature of the equipment shelf and the radiators were monitored to ensure that freon was freely flowing in the loop.

The initial temperatures of the spacecraft controlled by the HRS were as predicted. The radiator temperature was -4 C while the lander electronic shelf temperature was around +5 C. The temperature difference between the shelf and the radiator for the no bypass flow was about 10 C as was predicted from the analysis and measured during the thermal vacuum test. At this shelf temperature, the thermal control valve did not bypass the radiator as was designed. The radiator temperature, which is a function of the distance from the sun and the sun angle on the spacecraft, dropped as the spacecraft cruised towards the Mars. A temperature profile of the shelf and the radiator temperature for one hour duration is given in Figure 5 when the spacecraft was thirty days into the flight.

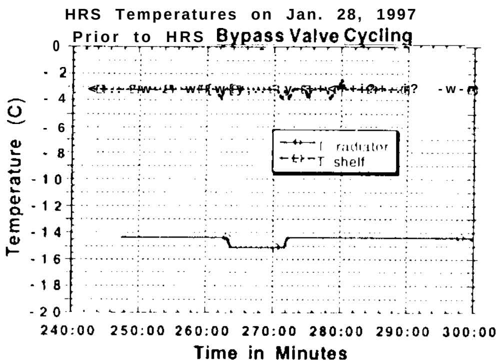

Figure 5. HRS temperature **Prior to Bypass Valve Cycling**

About forty-five days into the mission the radiator temperature dropped below -12 C and the lander shelf temperature dropped below O C. At this temperatures, the freon leaving the shelf will be below O C and would make the thermal actuator open and partially bypass the radiator. **A** temperature profile of the shelf and the radiator temperatures for one duration is given in Figure 6 when the thermal control valve is partially open. The small cyclical fluctuation in the shelf temperature is because the valve actuator is continuously trying to adjust to the freon temperature. This was similar to what was seen during the system thermal vacuum tests.

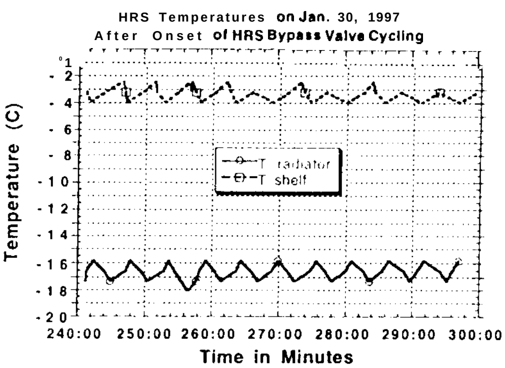

Figure 6. HRS Temperatures after the Onset of Bypass Valve Cycling

The radiator temperature has continued to gradually drop and at this writing it is at about -40 C. When the spacecraft is near Mars, the radiator temperature is expected to be around -70 C. The temperature of the radiator and the shelf for the first I I O days of the mission is shown in Figure 7.

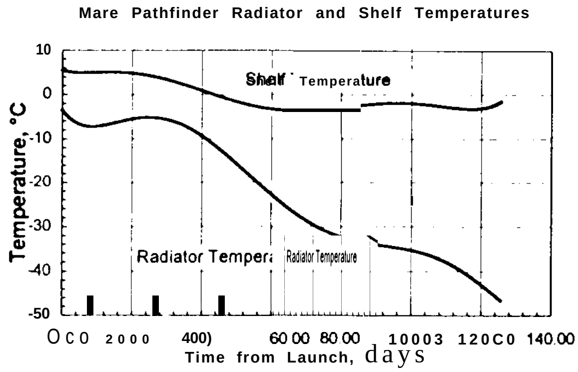

Figure 7. Radiator and electronic Shelf Temperatures for the First 125 days after Launch

Cycling of the Backup Pump

Based on experience with the life testing of the pump loop it was recommended that the idle pump be turned on once a month[4]. This is due to the reason that any small particulate that are present in the freon flow may collect around the idle backup pump. Any excessive accumulation of particles in the hydrodynamic journal bearing gap may lead to a large starting current. Turning the idle pump on once a month would ensure that the particles are flushed through the bearing gap by the freon flow. The temperatures of the radiator and the shelf during the pump cycling is shown in Figure 8. The current draw of the spacecraft during the cycling of the pump is shown in Figure 9.

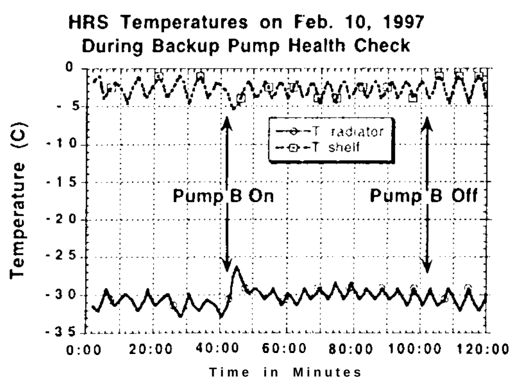

Figure 8. Temperature of the Radiator and the Electronic shelf during Pump cycling

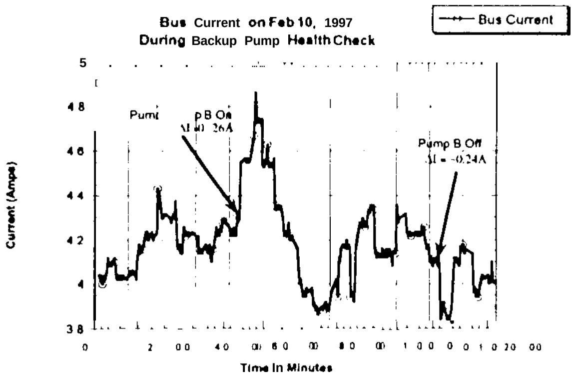

Figure 9. Current Draw of the Spacecraft during the Pump Cycling

FUTURE APPLICATIONS FOR ACTIVE THERMAL CONTROL SYSTEMS

During the preliminary design stages of the Pathfinder spacecraft, the HRS was based on a passive system that **would transfer the heat from the lander electronic** shelf to an external radiator. However, prior to the critical design stage, it became increasingly evident that the passive system based on heat pipes would lead to an HRS design which was massive and very difficult to implement. Further, because of the assembly and disassembly of the spacecraft during integration, the heat pipe based HRS **would have made it very difficult to integrate and test. Because of these reasons, an active** cooling system consisting of a mechanically pumped **cooling loop was investigated and** selected for the Pathfinder HRS. Because of the schedule constraints of less than two years to design, build, test, and install on the spacecraft, there was not much effort spent on optimizing the design and fabrication in terms of mass and performance.

With the successful demonstrate ion of the mechanically pumped cooling loop system on Mars Pathfinder, there is now a large interest among the spacecraft designers to consider active thermal control system for future spacecraft. Mechanically pumped cooling systems can be beneficially used on spacecraft with a mission characteristics similar to Mars Pathfinder mission. The key thermal characteristics of the Pathfinder missions are: the one year duration, temperature range of-40 C to 50 C for the pump hardware and up to -100 for the working fluid, fluid operating pressure of less than 100 psia, a pressure differential of4 psid in the loop, a heat transfer capacity of 150 Watts with a 10 C temperature difference between the heat source and the radiator, an electrical power of 10 Watts, and a cooling system mass of about 18 kg on a 800 kg spacecraft.

Based on our experience with the design and fabrication of the cooling loop on the spacecraft and the **life test that is being conducted** at JPL, we feel that the future similar pumped cooling loops can be easily built for a 30% mass. Any further improvements in the pumped loop requires detailed design, analysis, and testing of the pumped loops. The life and reliability of the pumped loops can be easily demonstrated for duration two to three years. The electrical performance can be easily improved by 200/o; any further improvements need detailed investigations. There are several technology improvements that can be made in the accumulator and motor control electronics that would cut the mass further by 20°/0.

Some of the spacecraft missions the active thermal control loop is being considered are the Mars Exploration program, new outer planet exploration missions, microspacecraft missions. Most of these studies are at the conceptual or preconceptual stages. It is expected that in the next three to four years an active cooling loop would be carried on one of these actual spacecraft for these missions. Another application the active cooling loop is ideal candidate is for the common thermal bus design for spacecraft. With such a system, a robust thermal system would be available to future spacecraft and make the spacecraft design and operation significantly easier than it currently exists.

CONCLUSIONS

An active thermal control system has been successfully designed, built and flown on Mars Pathfinder spacecraft. It has been demonstrated that such a mechanically pumped cooling system can be reliably operated for missions of one year duration. The flight thermal performance of the spacecraft has been excellent. The flight performance matches closely with the analytical predictions and measurements made during ground tests. The thermal control design and performance of a spacecraft with such a robust thermal control system is more reliable and predictable than a design based on a passive system.

The flight performance of the mechanically pumped cooling loop has demonstrated that such active thermal control systems can be reliably used on one year duration space missions. With further design development and more life testing of these loops will result in mechanically pumped loops being viable candidates for missions lasting several years.

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